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APPLICATION OF HOT-WIRE ANEMOMETRY FOR TWO-PHASE FLOW MEASUREMENTS SUCH AS VOID FRACTION AND SLIP VELOCITY

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ABSTRACT

Visual observations of two-phase flow (liquid and gas) have shown that complicated distributions of gas and liquid are present. Information on the void (gas volume) distribution and velocities of the phases in systems where flow visualization is impossible is needed for both hydrodynamic and heat-transfer analyses.

Described herein is a hot-wire anemometer technique which is capable of detecting the void distribution. Comparison was made of the hot-wire anemometer output with high-speed motion pictures of the flow patterns. It was observed that the anemometer output could be correlated with the high-speed pictures.

Statistical analysis of the anemometer results makes it possible to give valuable information concerning the two-phase flow patterns within a metal tube or channel.

AUTHOR

INTRODUCTION

In the study of two-phase flow, it is important to have information about flow regime, void distribution, and local velocities. In general, the void fraction is either measured experimentally or computed using information about quality and slip velocity. The experimental techniques for determining void fraction include the use of gamma-ray attenuation, X-ray attenuation, visual observation, propagation of sound waves, and more recently, the use of a conductance probe. Among these methods, the attenuation methods have been used most widely (e.g., ref. [1][1]), but they have poor accuracy and are unable to give local and instantaneous information. The visual method is not feasible for most practical purposes. The method using propagation of sound tends to interfere with the system. The more promising one is the recently developed method of using an electrode probe to measure conductivity between the wall and the probe [2]. Such a probe, being traversed in a channel, can measure the spatial distribution of void. However, the probe is useless in mist flow, since there is still no electrical continuity between the probe and wall even when a droplet strikes the probe. None of the above methods can give information about detailed structure in two-phase flow. None of these methods can yield information about flow velocities.

The purpose of this paper is to report a new technique for two-phase flow measurements using hot-wire anemometry, which yields information about void fraction, vapor and liquid velocities, turbulence level, etc. High-speed photography was used to check the validity of various measurements, including flow-pattern identification, void-fraction measurement, and flow oscillation.

Theoretical Background

Hot-wire anemometry has been widely used in the study of hydrodynamics.

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[1]Numbers in brackets designate References at end of paper.

The technique has been highly developed (e.g., [3]). Later, Ling [4] developed a hot-film anemometer which uses a hot film on a cylinder instead of a hot wire to give higher sensitivity. Recently, Fingerson further improved the hot-film anemometer technique [5].

In conventional single-phase flow measurement, the application of the hot-wire anemometer is based upon the fact that the heat-dissipation rate from the probe varies with the flow velocity. According to McAdams [6], the heat-transfer correlation for the cooling of a cylindrical body by a cross-flow is of the following form:

$$\left(\frac{hD}{K_f}\right)(Pr)^{-0.3} = 0.35 + 0.56\left(\frac{Du\rho_f}{\mu_f}\right)^{0.52} \tag{1}$$

More recently, Collis and Williams [7] recommended

$$\left(\frac{hD}{K_f}\right)\left(\frac{T_f}{T_\infty}\right)^{-0.17} = A + B\left(\frac{Du\rho_f}{\mu_f}\right)^{n} \tag{2}$$

with

	$0.02 < Re < 44$	$44 < Re < 140$
n	0.45	0.51
A	.24	0
B	.56	.48

where

D cylinder diameter

h heat-transfer coefficient

K_f thermal conductivity of fluid evaluated at T_f

Pr Prandtl number of fluid evaluated at T_f

Re Reynolds number, $Du\rho_f/\mu_f$

T_f arithmetic mean temperature between cylinder surface and ambient

T_∞ ambient temperature

u velocity of flow normal to the cylinder

μ viscosity of fluid evaluated at T_f

ρ_f density of fluid evaluated at T_f

Thus, the heat-transfer coefficient varies directly with the square root of the velocity (approximately). It is also clear from Equations (1) and (2) that the heat-transfer coefficient depends strongly upon the physical properties of the fluid flowing past the cylinder. In general, the physical properties of a fluid in the liquid state are so different from those in the vapor state that the heat-transfer coefficient for the liquid is two or three orders of magnitude higher than that for the vapor at the same velocity. Thus the rates of heat dissipation from a hot-wire probe exposed alternately to liquid and vapor are, in general, far enough apart so that the variation due to the change of state cannot be confused with that due to the velocity fluctuation. The large differences in heat-transfer coefficient between the liquid and the vapor states is the basis for the application of hot-wire anemometry to the two-phase flow measurement. In other words, from the level of heat-dissipation rate, it can be determined whether a liquid or a vapor phase is passing the probe. When the phase is known, then the velocity of the fluid passing the probe can also be determined from the power input to the probe if the temperature difference between probe and fluid is known. Theoretically, the velocity could be determined from Equation (1). However, in reality, calibration is needed for reliable results.

DESCRIPTION OF MEASURING TECHNIQUE

The basic components for the two-phase flow measurement with anemometry consist of a hot-film anemometer, a control unit, and a recording unit. The hot-film probe was held at a preset temperature (in general, about 30° F above the saturation temperature) by the control unit, and the recording unit recorded the time-trace of power input to the probe. From this power input trace, the velocity and the physical state of the fluid passing the probe at each instant can be determined.

The hot-film sensor was a glass cylinder 0.003 inch in diameter and 1/8 inch long (Fig. 1). A thin coating of platinum was deposited to form a conductive film, and the sensor was then dip-coated with a layer of epoxy resin to eliminate short circuiting in water. The glass cylinder was mounted at each end of two copper legs $1\frac{1}{2}$ inches long, which in turn were connected to the control unit through a coaxial cable. For the present study, the probe was located in the center of the heating tube with the sensor cylinder transverse to the flow. A commercial control unit was used. The control unit and circuitry were essentially the same as that described by Fingerson [5]. A schematic of the circuit diagram is shown in Fig. 1. The resistance of the probe was set at a value corresponding to a desired probe temperature. If the probe resistance began to depart from the preset value due to a change in temperature, the control unit would respond with a change in current to maintain a constant probe temperature.

The power or voltage input to the probe was recorded on an oscillograph chart. Through a calibration trace of power as a function of flow velocity at various temperatures of probe and flow, the fluid state and the fluid velocity are determined. The probe temperature is preset to the desired value by setting the probe resistance, while the fluid temperature is determined with a thermocouple.

The selection of probe temperature is important. In the convective regime it is obvious that the higher the difference between the probe temperature and the bulk temperature the better is the sensitivity. However, there is definitely an upper limit in probe temperature for the case of two-phase flow. Setting the probe temperature too high (e.g., 100° F above the saturation temperature), may result in film boiling on the hot wire when liquid is passing the probe. As a result, the probe would continuously "see" vapor phase regardless of whether vapor or liquid is passing it. If the probe temperature were somewhere between 10° to 100° F above the saturation temperature, nucleate boiling on the probe may take place. It is very desirable to have nucleate boiling occur if the only purpose of hot-film anemometry is to determine the void fraction, since the difference in the heat-transfer coefficient between the two phases will be very large. However, if information about liquid velocity is desired, nucleate boiling on the probe should be avoided, since in the nucleate boiling regime the velocity effect on heat-transfer coefficient is usually overshadowed by the strong agitation effect of ebullition. In such a case, the probe temperature should be limited to not more than about 10° F above saturation temperature.

For the present study, the flow channel was a glass heating tube as described in reference [8]. For each run, the steam and the hot water were premixed to give the desired flow pattern. A high-speed motion picture camera (capable of 5000 frames per sec) was used to photograph the flow across the probe. The oscillograph trace and the high-speed motion pictures were provided with a common time scale through simultaneously triggered 60-cps time tracers so that the recordings on both could be matched against each other.

To compare the results, the films were analyzed frame by frame to determine the time and the duration of each bubble passing the probe, and the film record was then matched against the tracings on the oscillograph record to determine whether the hot-wire anemometry system was capable of sensing all the events as observed through photographic study.

APPLICATION AND EXAMPLE

From the comparison between the motion pictures and the oscillograph trace of power input to the probe, it was found that hot-film anemometry is capable of giving the following information:

1. Qualitative determination of flow regime. - The oscillograph tracings for various flow regimes are different enough so that the nature of the flow pattern can be determined by observing the tracing. Examples are shown in Figs. 2 to 5. Also shown, whenever feasible, are strips of high-speed motion pictures taken in the same runs.

The tracing in Fig. 2 indicates that the flow was in the bubbly regime. The probe was exposed to liquid most of the time, but an occasional bubble passed to give a "blip" of short duration. From the duration of such a blip and the bubble velocity, the length of a bubble can be determined. In bubbly flow, the bubbles are roughly spherical in shape with diameters that are less than the pipe diameter so that this regime corresponds to a bubble length that is much less than the pipe diameter. Fig. 3 illustrates the type of trace obtained in slug flow where the duration for each bubble passing the probe is very long. Knowing the velocity of bubbles, it is clear that the bubble length is several times larger than the pipe diameter. This is characteristic of slug flow.

Fig. 4 is the tracing for a mist flow with lean droplet content. The flow was predominately vapor, with occasional bombardment by a droplet, which is indicated by a blip toward the liquid side. Photographs are not shown since it is very difficult to catch the image of a droplet bombarding the probe. Fig. 5 is the trace of a mist flow with very rich droplet content. Because of the high frequency of bombardment of the probe by the droplets, the fluctuations of the trace were predominantly tending toward the liquid side. Only occasionally was the probe completely dry as indicated by a large blip toward the vapor side of the trace. Such a trace sometimes is easily confused with that for bubbly flow (see Fig. 2). However, by closer examination of the frequencies of and/or the amplitudes of the trace fluctuations in Figs. 2 and 5, the difference between the traces of the rich mist flow and bubbly flow can still be discerned. Sometimes, differentiation between these two flow regimes can be achieved with the aid of other information such as quality or past history of flow patterns, etc. Nonetheless, the possibility of confusing rich mist with bubbly flow is a drawback of the application of the hot-film anemometer to two-phase flow. One way to minimize this difficulty would be to use a very small probe.

It is not possible to tell by a probe in the centerline whether an annular flow is achieved; however, if the probe could be traversed across the tube, an all-liquid tracing near the wall together with a vapor-dominating tracing at the center of the tube should indicate an annular flow.

2. Quantitative determination of the void fraction. - The fraction of the total time during which the probe detects the vapor phase can be considered as the local void fraction. Therefore, if the times for each void to pass the probe are summed up and then divided by the total time span, it should give the local void fraction. Fig. 6 shows the void-fraction measurement for a slug flow which was based upon the original trace as shown in Fig. 3. The reduced data are shown on a time scale on the X-axis. The corresponding data reduced from high-speed motion pictures are shown on the same time scale on the Y-axis. A perfect matching would be lying on the 45° line; this probably is due mainly to the uncertainty in determining the tail end of bubbles from the motion picture. The void-fraction measurements shown in Fig. 6 are also tabulated in table I.

It is clear that, if a traversing probe were used, a radial distribution of void fraction could be measured with good accuracy. Such technique should be superior to the gamma-ray attenuation method, which is most commonly used. In general, the gamma-ray method measures only the time and space averaged overall void fraction at one section. Even if a scanning technique could be used to obtain radial distribution, the error would be generally rather high. The difference between the anemometry and gamma-ray attenuation methods is that the hot-wire probe records the true local variation of the void, while the gamma-ray method can only detect the variation of the total void along the path between the source and the detector. With the anemometer, the local void fraction is determined by integrating the time fraction in which the probe was exposed to vapor phase, while in the gamma-ray method the local void fraction can only be obtained through differentiation, which usually would result in a much larger error.

3. Bubble influence. - Fig. 7(a) shows the oscillograph tracing obtained during the passage of a bubble. It is interesting to notice that before the probe detected the bubble interior, it actually detected first an increase of liquid flow velocity. The liquid apparently was pushed upward by the rising bubble. This region is equivalent to the stagnation point on a stationary sphere in a flow field. However, to prevent possible confusion, the liquid which is pushed up by a bubble can be called the vanguard of the bubble. As expected, the tracing also shows the wake of a bubble. The turbulence level in the wake was greater than that of the main flow velocity. This is also shown in figure 7(a). Fig. 7(b) (same oscillograph trace as Fig. 3) shows the trace when a bubble bypassed the probe without actually touching it. Thus the hot-film anemometer is very suitable for studying the influence of bubbles on the flow characteristics.

4. Flow oscillation. - Fig. 8 shows that the flow is under pulsation. The points A and B were also checked against motion-picture results, and the difference was less than 1/60 second. Thus the hot-wire anemometer can be used to determine whether a flow instability has set in, and if so, the frequency of pulsation.

In addition to the above measurements, the authors found that the following measurements could also be made, however, due to the scope of the problems, discussion here will be limited to the qualitative description of feasibility of each application.

5. Bubble rising velocity. - Since the probe also sense flow velocity, the velocities of both bubbles and the liquid flow can be measured. The rising

velocity of bubbles (with respect to the liquid flow) can be determined. Such information would be useful in determining slip ratio, or checking some of the existing correlations for bubble rising velocity.

6. Turbulence level. - As all the oscillograph tracings show, there are local small-amplitude fluctuations that are due to turbulence. An accurate tracing can be used to determine the turbulence level both in the liquid phase and the vapor phase and the effect of one phase upon the other.

7. Determination of quality. - A very important application of hot-film anemometry is to determine the quality of a two-phase flow. This may seem like a reversal of the general practice. In the past, for a boiling two-phase flow, the quality that was computed was first based upon thermodynamic equilibrium; then a slip ratio was assumed or estimated; and finally the void fraction is computed. However, it has been found by many researchers [8, 9, and 10] that thermodynamic equilibrium actually is not necessarily achieved. In fact, it is more often the case to have nonequilibrium than equilibrium. Thus, the problem is to estimate the quality when thermodynamic equilibrium is not achieved. Since the hot-film anemometer is capable of measuring both void fraction and slip velocity, it is possible to compute quality. If enough information about quality in nonequilibrium state is accumulated to cover a range of conditions, it would help the "art" of estimating quality.

DISCUSSION

In the last section, some of the potential uses of hot-film anemometry were suggested. In this section, the overall merits and limitations of hot-film anemometry will be mentioned.

1. Merits

(a) It gives local detailed structure of two-phase flow.

(b) The probe gives high-frequency response. A time recording shows the history of flow passing a probe.

(c) It is versatile in application.

(d) It is easy to install and simple to operate, and it can be installed in any heating channel.

2. Limitations

(a) The fluid must be electrically nonconductive. For a conductive fluid, an insulating coating should be applied to the probe. Sometimes it might be difficult to find an insulating coating that would remain intact while not greatly impeding the frequency response.

(b) The probe is rather fragile.

(c) If the droplet or bubble is significantly smaller than the probe dimensions (length), the change in power input when only part of the probe is bombarded by the dispersed phase may not be significant enough to show variation on the trace.

(d) There is a possibility of confusing rich mist flow with bubbly flow.

3. Possible modifications

(a) The probe can be made of other material, such as a very fine wire of tungsten or platinum. The hot-wire probes are sturdier than the hot-film probe made of a platinum-coated glass cylinder, which was used in the present study.

(b) The probe can be made in another geometry, such as a sliding rod with a small section as the heating element.

(c) An "on-off" switch circuit can be incorporated in the circuit to automatically integrate all the small void intervals to give a mean void-fraction reading.

(d) The probe should be made as small as possible to minimize limitations (c) and (d).

CONCLUSION

The hot-film anemometer technique was used to make two-phase flow measurements. High-speed motion pictures were used to check the reliability of the hot-film anemometer. The results show that hot-film anemometry can perform versatile duties in two-phase flow measurements including: void fraction, identification of flow regimes, flow oscillation, bubble influence, etc. Qualitative results also indicate the possibility of using such a probe to determine slip ratio and vapor "quality" in nonequilibrium state.

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TABLE I. - COMPARISON OF VOID-FRACTION RESULT BETWEEN THE DATA FROM

MOTION PICTURES AND OSCILLOGRAPH TRACINGS

	Motion pictures				Tape			
Bubble number	(1) Bubble enters, number of 1/60-sec cycle	(2) Bubble leaves, number of 1/60-sec cycle	Duration of bubble passing the probe, ΔC_b (2)-(1)	Summation of time that probe sees the bubbles, $\Sigma\,\Delta C_b$	(3) Bubble enters, number of 1/60-sec cycle	(4) Bubble leaves, number of 1/60-sec cycle	Duration of bubble passing the probe, ΔC_b, cycle, (4)-(3)	Summation of time that probe sees the bubbles, $\Sigma\,\Delta C_b$, cycle
1	1.0	2.7	1.7	1.7	0.8	2.1	1.3	1.3
2	3.7	4.3	.6	2.3	3.1	4.3	1.2	2.5
3	7.5	8.2	.7	3.0	7.5	8.1	.6	3.1
4	9.5	10.3	.8	3.8	9.7	10.4	.7	3.8
5	10.5	12.8	2.3	6.1	10.5	17.5	2.0	5.8
6	15.0	15.4	0.4	6.5	15.0	15.4	0.4	6.2
7	17.7	18.8	1.1	7.6	17.5	18.5	1.0	7.2
8	20.1	21.0	1.0	8.6	20.0	20.9	.9	8.1
9	23.0	23.9	.9	9.5	22.6	23.4	.8	8.9
10	25.3	25.9	.6	10.1	25.3	25.9	.6	9.5
11	27.1	29.6	2.5	12.6	27.1	29.1	2.0	11.5
12	32.0	33.2	1.2	13.8	32.0	37.9	.9	12.4
13	34.4	34.9	.5	14.3	34.3	34.6	.3	12.7
14	36.0	36.7	.7	15.0	36.0	36.5	.5	13.2
15	38.0	39.0	1.0	16.0	38.0	38.9	.9	14.1
16	39.0	39.7	0.7	16.7	39.0	39.2	0.2	14.3
17	41.0	42.1	1.1	17.8	41.0	42.1	1.1	15.4
18	43.3	43.4	.1	17.9	43.8	44.0	.2	15.6
19	----	----	---	----	----	----	---	----
20	46.8	47.4	.6	18.5	46.5	47.2	.7	16.3
21	48.9	49.3	0.4	18.9	48.6	49.2	0.6	16.9
22	50.0	50.1	.1	19.0	49.9	50.1	.2	17.1
23	51.0	51.3	.3	19.3	50.9	51.3	.4	17.5
24	52.8	53.8	1.0	20.3	52.6	53.4	.8	18.3
Void fraction = $\Sigma C_b/C^*_{total}$ = 0.378					Void fraction = 0.344			

$^*C_{total}$ = total number of cycles.

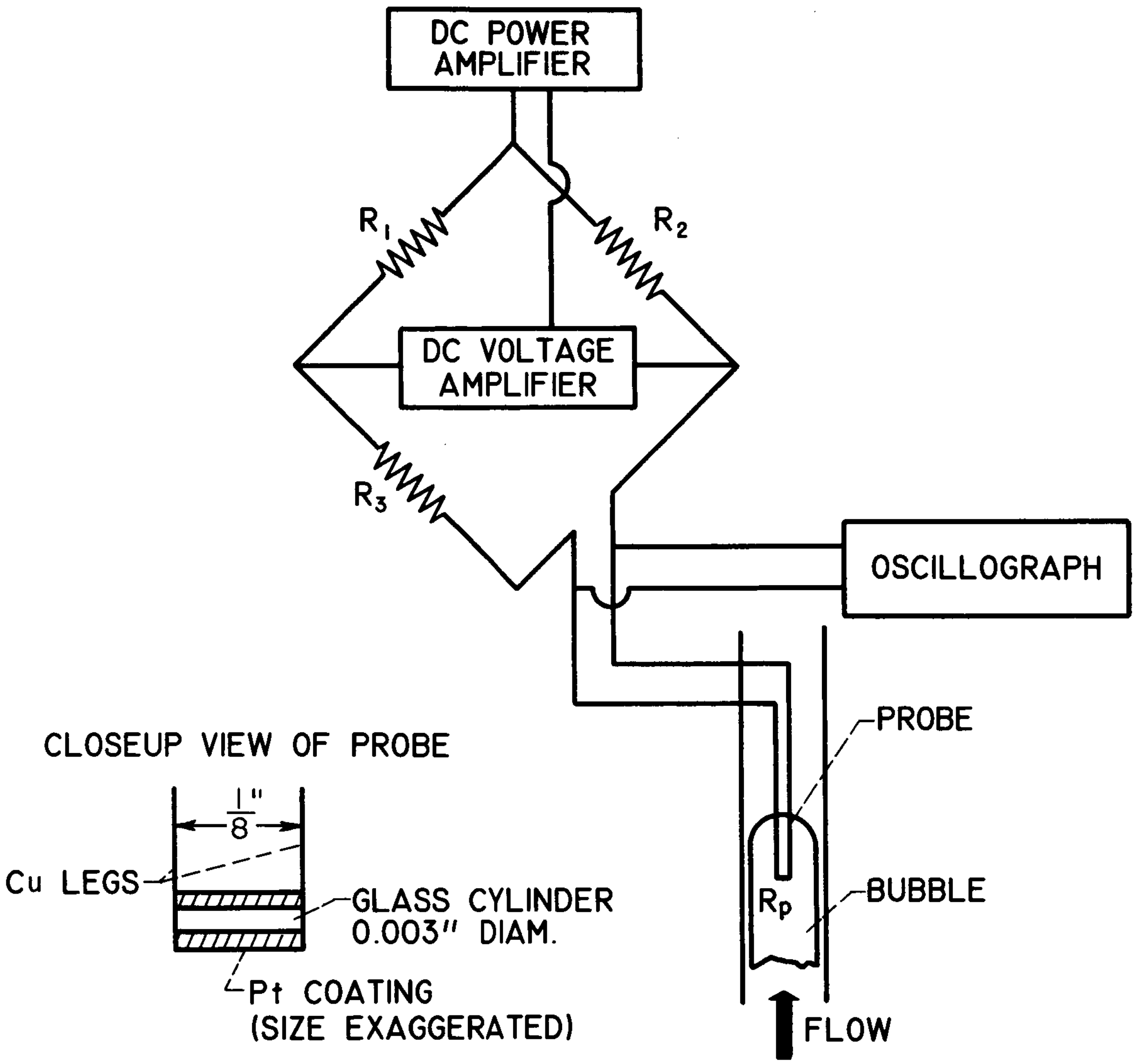

Fig. 1(a) Diagram For Hot-Film Anemometry.

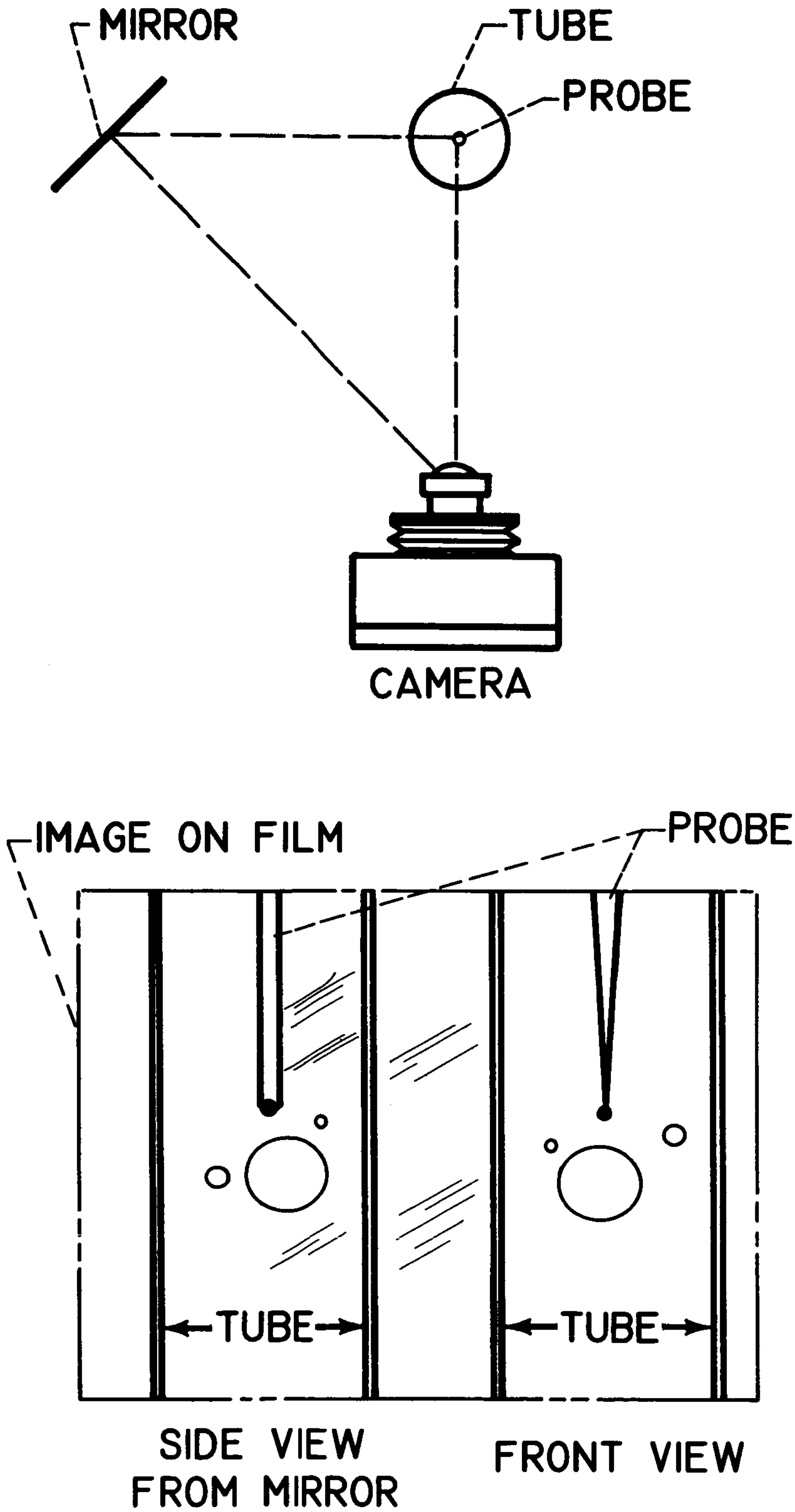

Fig. 1(b) Optical Configuration For Two-Phase Observation.

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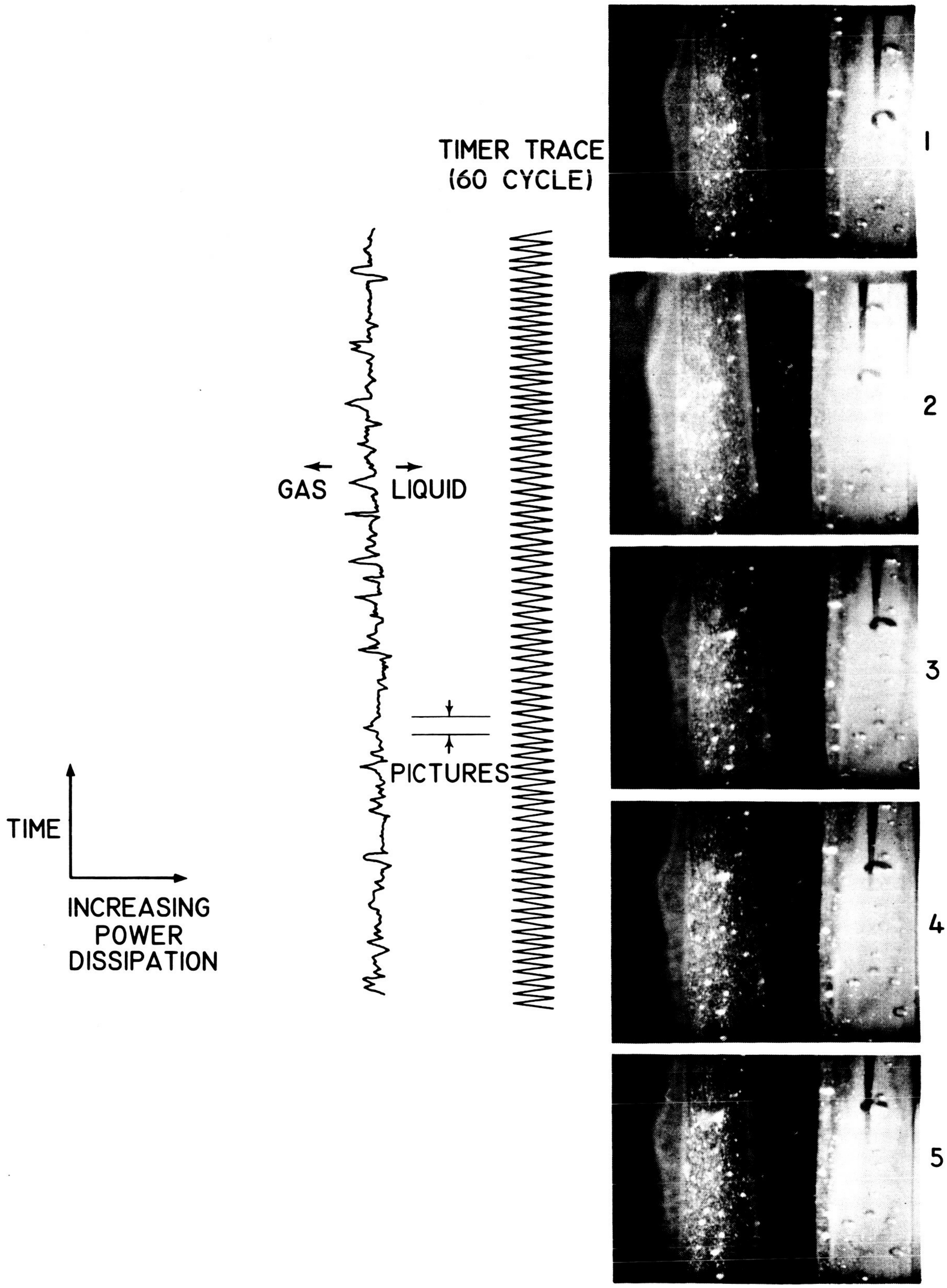

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Fig. 2 Bubbly Flow.

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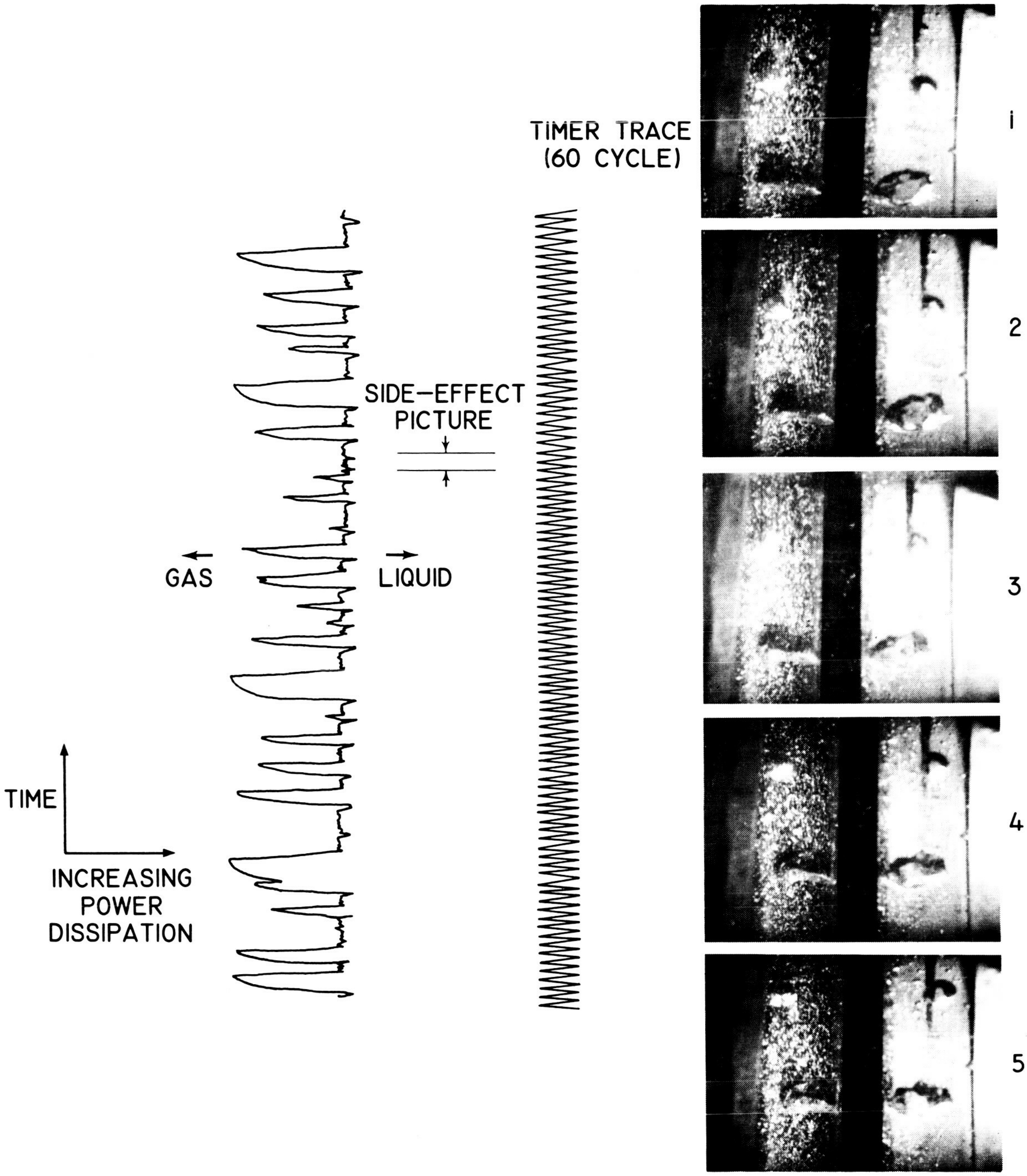

Fig. 7(b) Bubble Influence (Side Effect).

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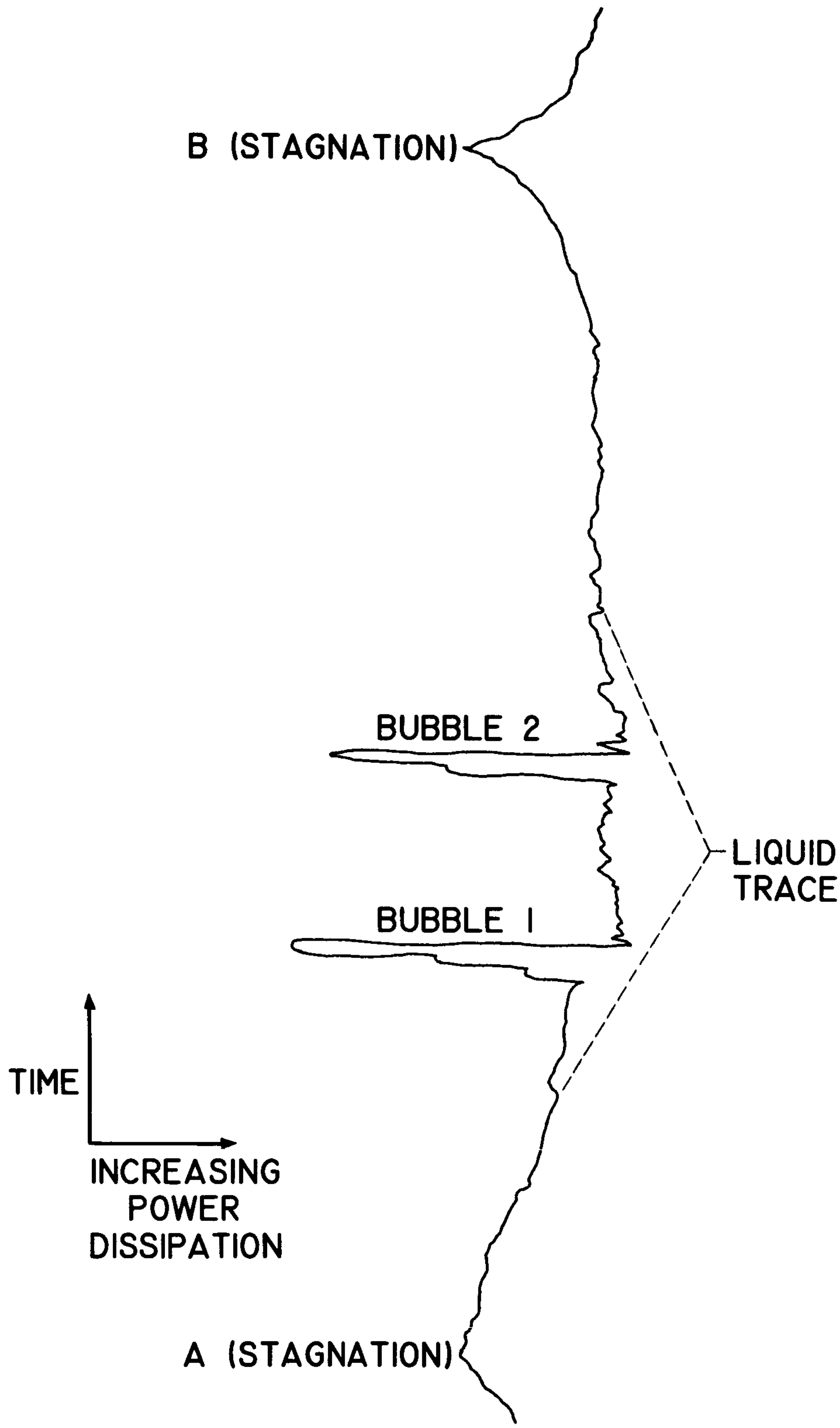

Fig. 8. - Oscillation of Flow.

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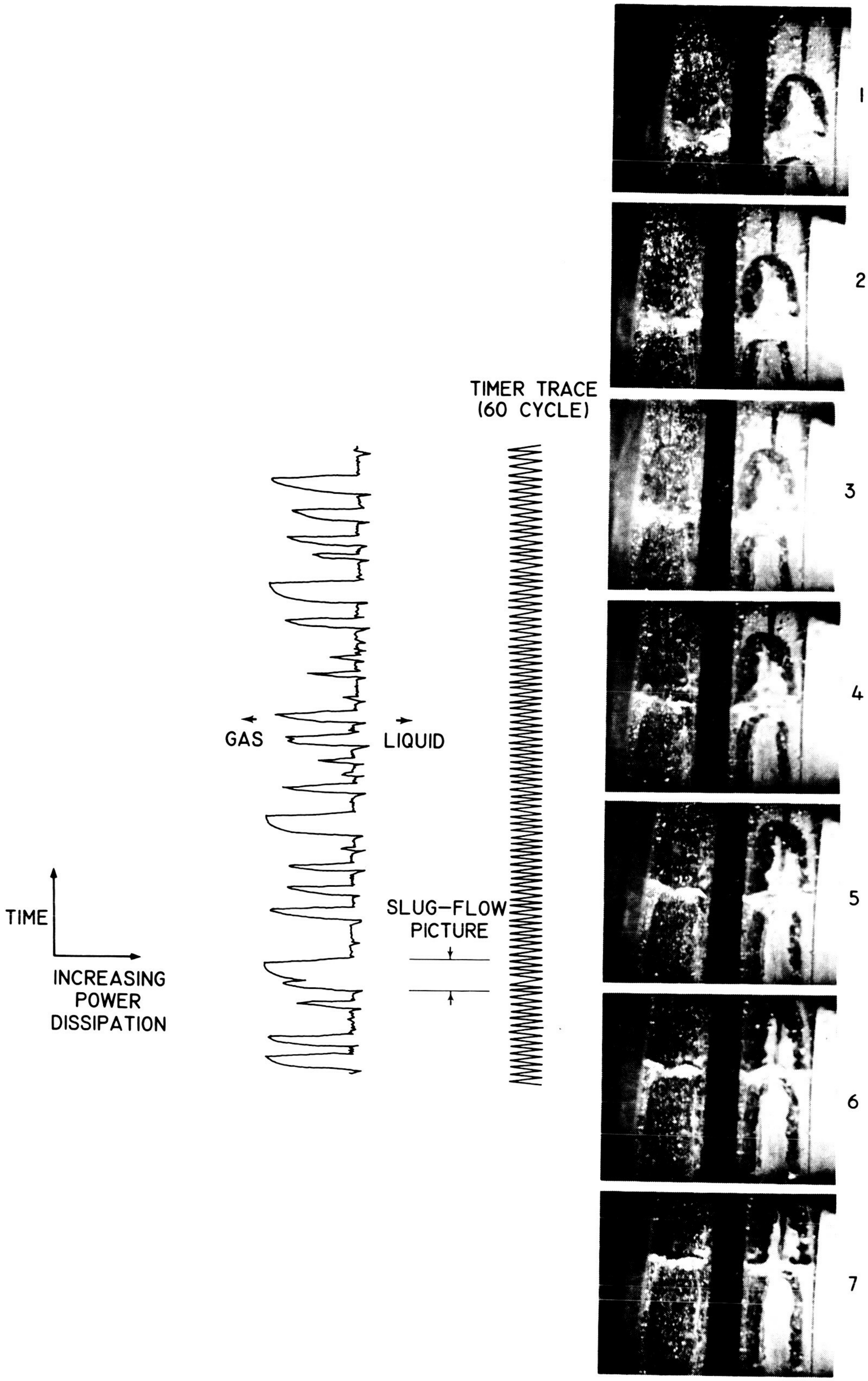

Fig. 3 Slug Flow.

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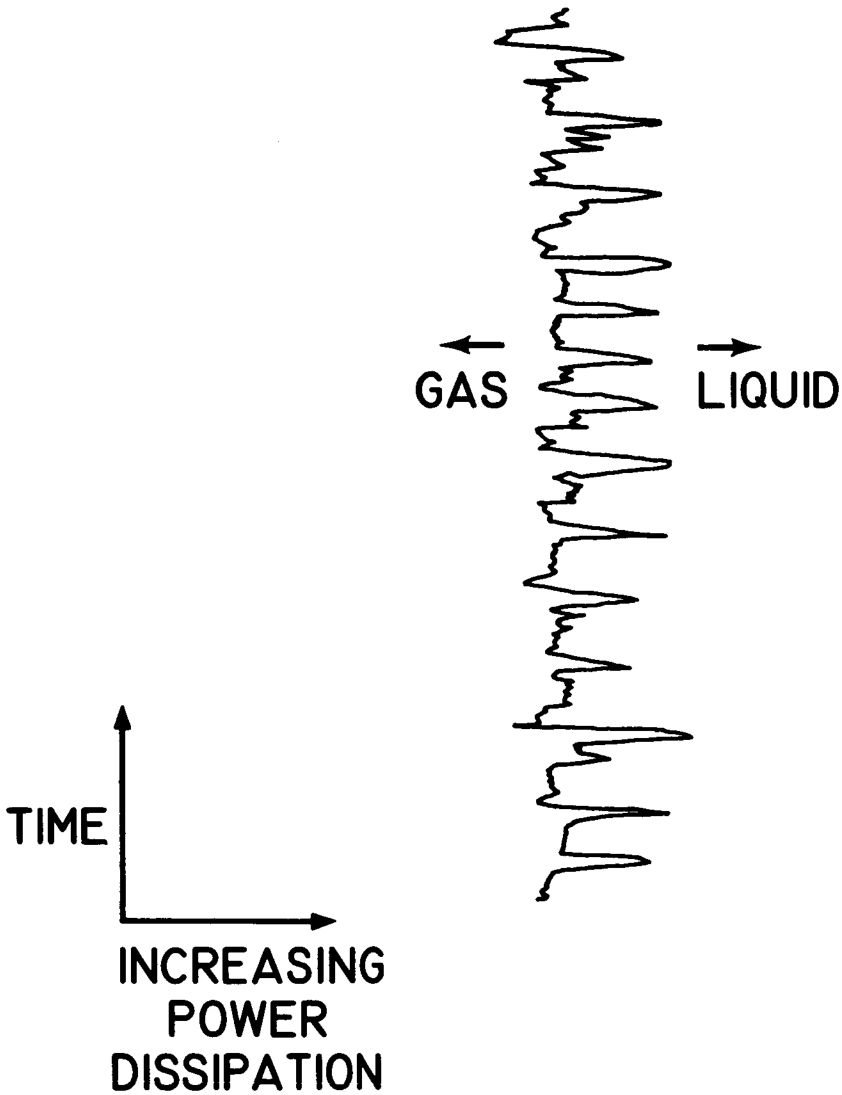

Fig. 4. - Mist Flow - Lean Droplet Content.

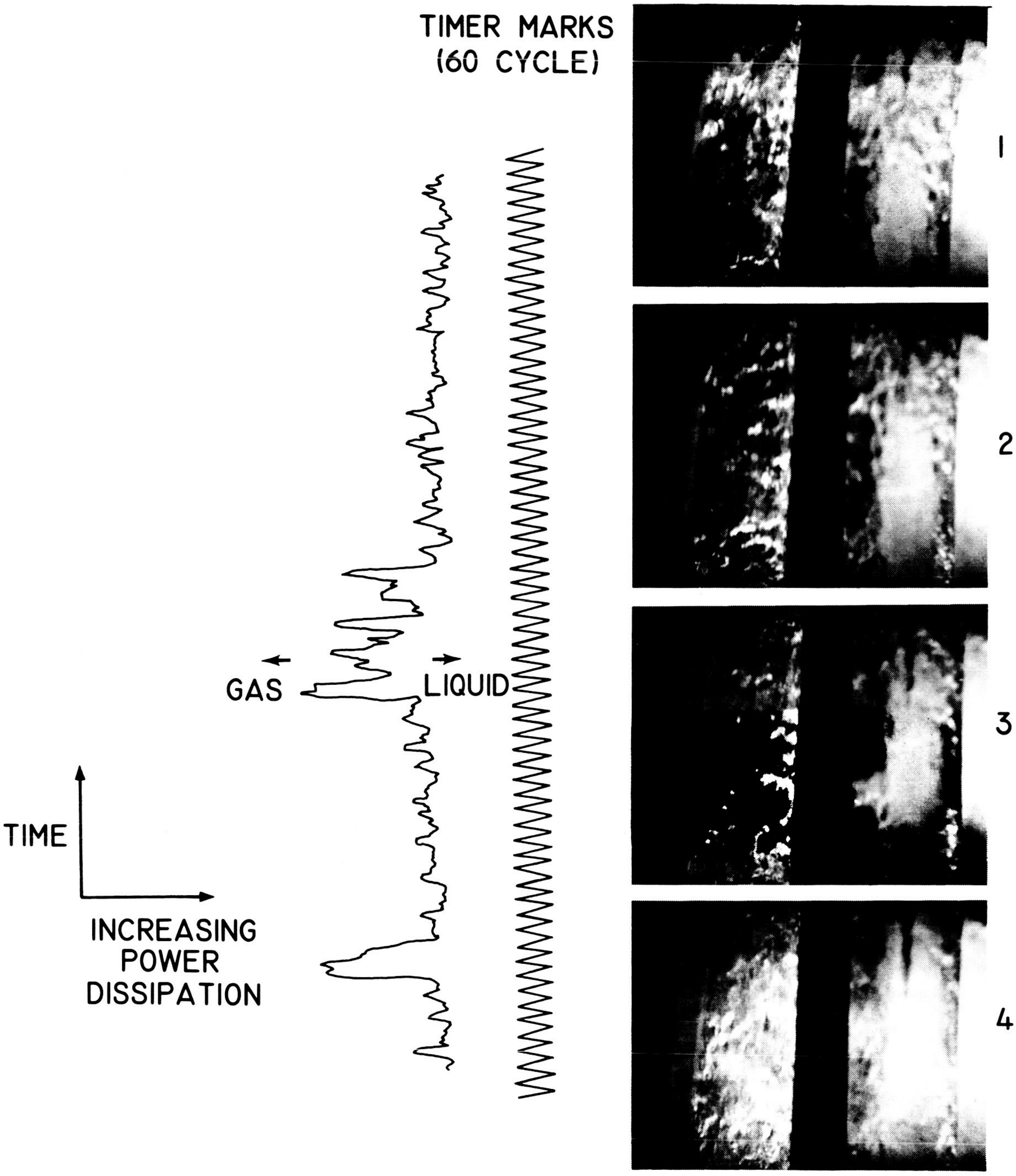

Fig. 5 Mist Flow-Rich Droplet Content.

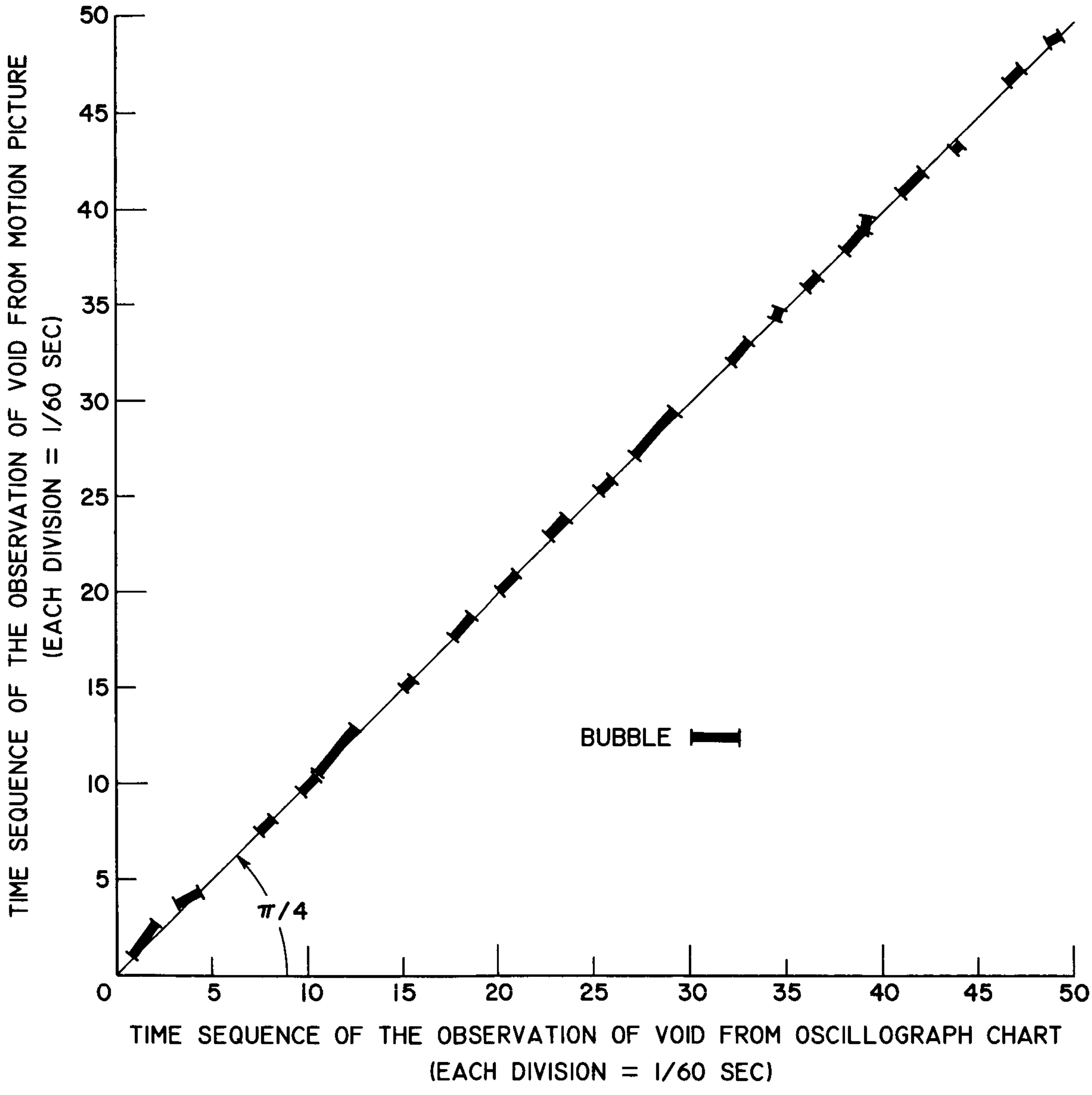

Fig. 6 Comparison of Void-Fraction Measruements Picture Against Hot-Wire Probe (Data From Table II).

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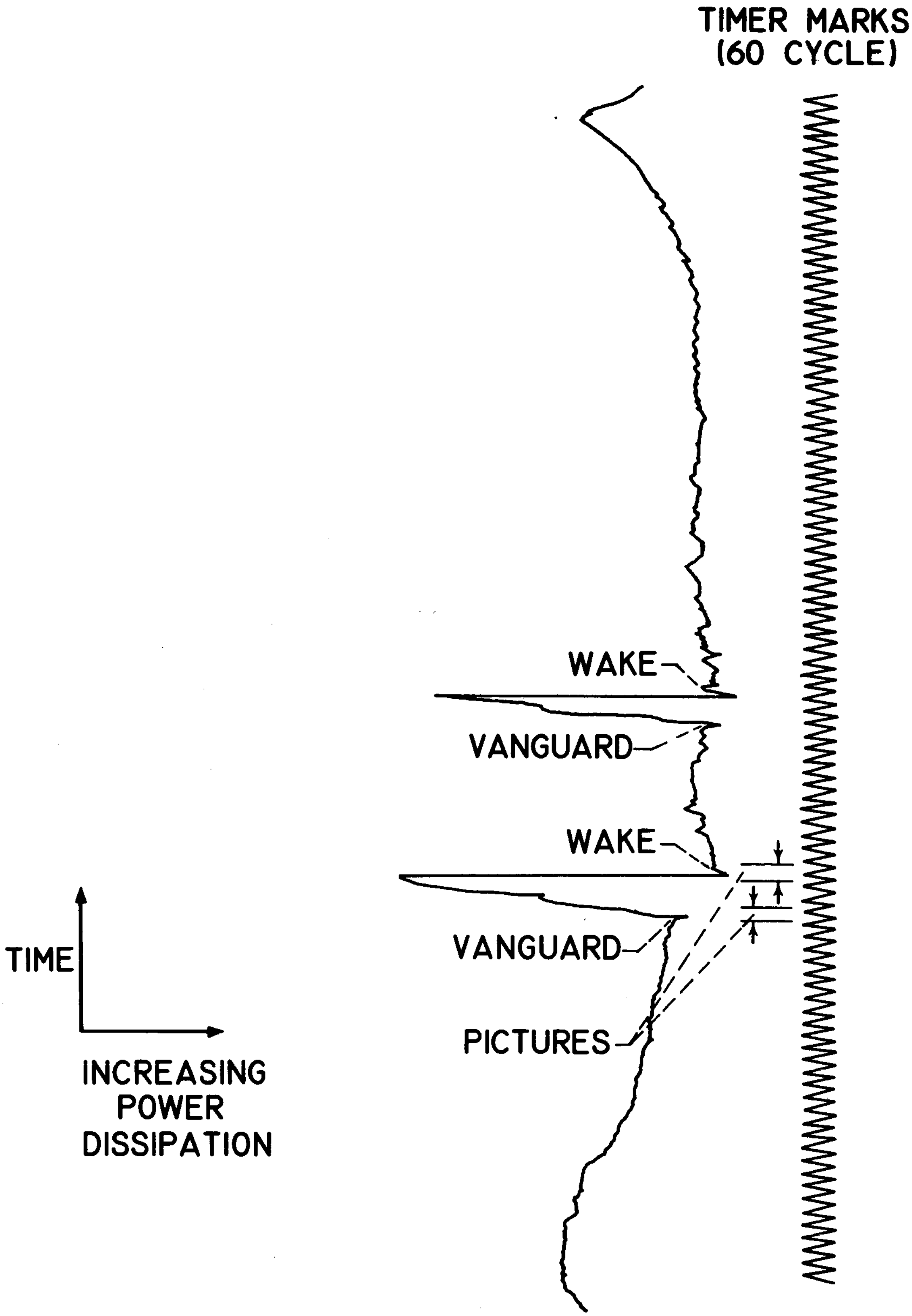

Fig. 7(a) Bubble Influence (Vanguard and Wake).

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Fig. 7(a) Continued. Vanguard of a Bubble.

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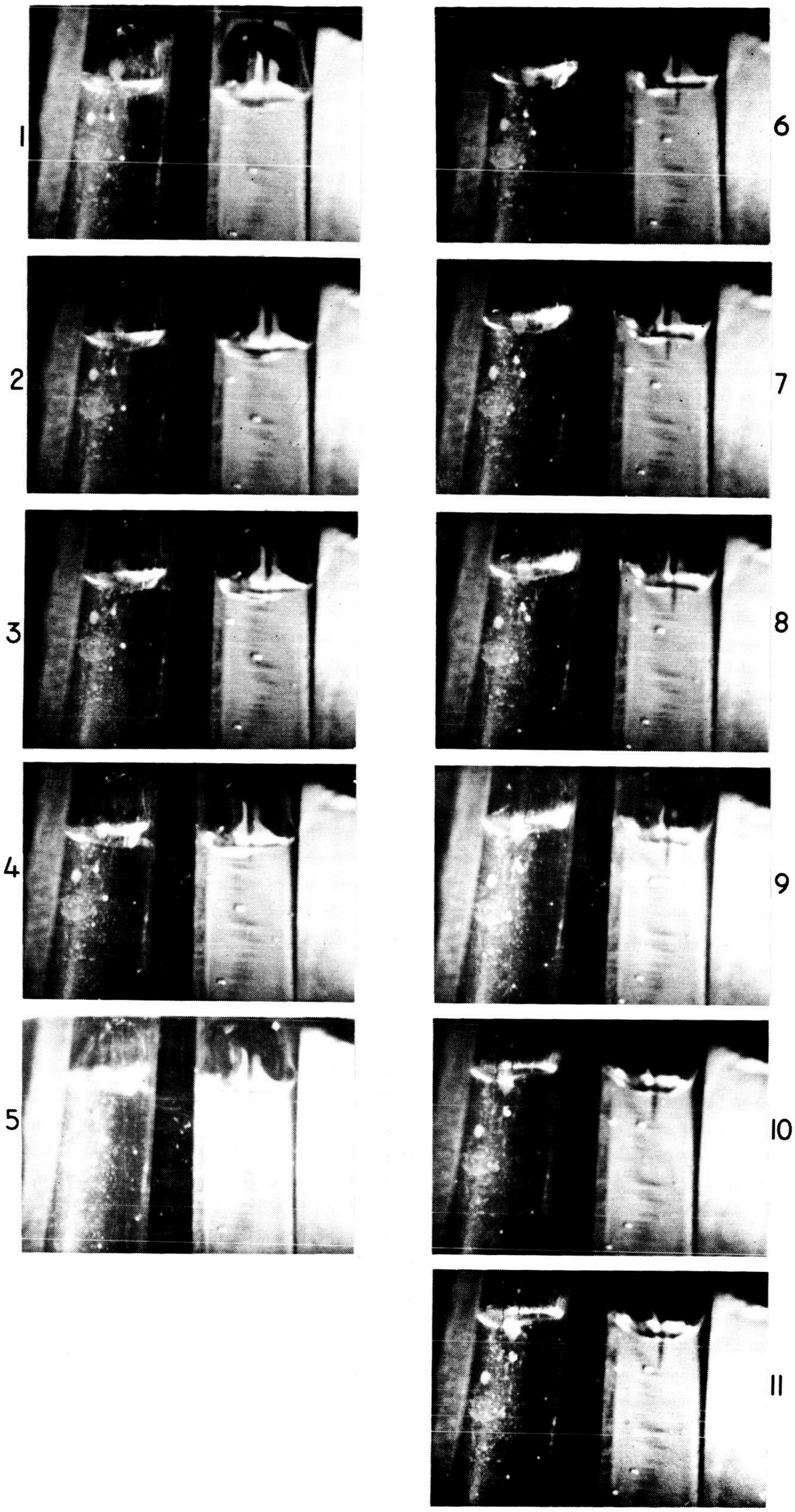

Fig. 7(a) Concluded. Wake of a Bubble. C-65934